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Dynamical modeling and experimental validation for tooth pitting and spalling in spur gears

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ABSTRACT

Dynamical modeling of a gear system with faults has been an important research topic for understanding fault features and their associated fault vibration mechanisms. Due to the complicated structures and intricate interactions between the components of the gear system, the fault vibration features and corresponding vibration mechanisms due to tooth pitting and spalling remain mostly unknown. This paper proposes a novel spur gear dynamical model, validated by various experimental tests, to analytically investigate the effects of tooth pitting and spalling on the vibration responses of a gear transmission. The proposed dynamical model considers the effects of tooth surface roughness changes and geometric deviations due to pitting and spalling, and also incorporates Time Varying Mesh Stiffness (TVMS), a time-varying load sharing ratio, as well as dynamic tooth contact friction forces, friction moments and dynamic mesh damping ratios. The proposed gear dynamical model is validated by comparison with responses obtained from experimental test rig under different conditions. Comparisons indicate that the responses of the proposed dynamical model are consistent with experimental results, in both time and frequency domains under different rotation speeds and fault severity conditions.

1. Introduction

Gear tooth pitting and spalling are typical tooth surface fatigue damages in a gear transmission. The appearance of tooth pitting is mainly due to prolonged, repeated heavy contact loads, whereby excessive local Hertzian contact fatigue stress flakes the asperity particles out of the contact surface [1–3]. The occurrence of pitting and spalling directly changes the tooth contact conditions by increasing the roughness of the tooth surfaces, modifying the tooth geometric profiles and reducing the effective tooth contact length. Due to the complicated structures and intricate interactions between the components of the gear system, fault vibration features and corresponding vibration mechanisms due to tooth spalling remain mostly unknown.

Dynamical modeling of gear transmissions with faults has been an important research topic for understanding gear fault vibration characteristics [4]. The vibration signals simulated by the dynamical model are noise and interference-free signals, which is often informative for analysis and understanding of fault symptoms and fault generation mechanisms. The solution of a dynamical model not only provides the time series of vibration displacements, velocities and accelerations of each component, but is also capable of providing the dynamic values of mesh forces, friction forces, friction moments, as well as changes in contact pressure, lubrication film thickness, damping ratio etc. All of these variables can be used to understand the vibration mechanisms of the system. Moreover, in the dynamic simulation, various fault types, severities and factors

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(e.g. Time Varying Mesh Stiffness (TVMS), friction, damping coefficient, etc.) can be easily isolated and controlled, which enables analysis of a wider range of scenarios than through experiments alone. The isolation of the possible impact factors helps to identify which parameters play dominant roles in controlling the vibration behaviors of gear transmissions. In addition, a good gear dynamical model (validated by experimental results) can be utilized as an excellent signal source for validating the effectiveness of fault detection and diagnosis methods or can be utilized to feed/train an artificial intelligence fault diagnosis algorithm [5].

Some work has been carried out in modeling the dynamical response of gear systems with tooth pitting or spalling. Choy et al. [6] proposed an analytical model to simulate the effect of tooth surface pitting and wear on the vibration response of a gear transmission. In their analysis, tooth pitting and wear were modeled as phase and magnitude changes of the gear mesh stiffness. Ma et al. [7] used a one Degree-of-Freedom (DOF) gear dynamic model of torsional vibrations to simulate the vibration response excited by local tooth spall. In their analysis, tooth spall was modeled as a reduction of TVMS. Abouel-seoud et al. [8] dynamically simulated the effect of a gear tooth crack, pitting and wear on the vibration response of a gear system under frictionless conditions. In practice, the appearance of pitting and spalling will directly result in a change in surface contact conditions [9,10]. The friction coefficient and forces vary significantly when gear teeth contact in a pitting or spalling area, thus friction effects cannot be neglected if an understanding of the effects of tooth pitting or spalling is desired. Jiang et al. [11] simulated the vibration response of a gear system with a tooth spalling defect. The dynamic model used in their analysis assumed a constant friction coefficient between the mating teeth and ignored the gear tooth sharing ratio. Jia and Howard [12] compared the differences between the vibration responses of tooth pitting and cracking through dynamical simulation. Recently, Liang et al. [13] simulated the vibration properties of a gear tooth pair with pitting distributed over multiple teeth, and also analyzed the statistical features of some common indicators.

The aforementioned studies on dynamic simulation of gear tooth pitting and spalling provide some important clues for understanding the vibration features of gear tooth surface defects. However, these studies are still inadequate to fully understand the complicated internal interactions between the mating gear pairs, as well as to explain the gear fault vibration mechanisms. The modelling of gear tooth pitting and spalling is complicated as many factors, such as the tooth geometric profile errors, TVMS, surface roughness and dynamic friction forces due to tooth spalling, should take into consideration in order to better understand the dynamic behaviors of a gear system under faulty conditions.

The validation of the dynamic model requires comparison of the model predictions with signals that can be experimentally obtained. Due to experimental limitations and application convenience, most vibration signals are obtained from the outside of the gearbox casing, instead of from the rotating gear pairs. Therefore, dynamic modelling of a gear system should also consider the effect of the gearbox casing in order to generate signals comparable to those obtained in practice. It is also worth mentioning that the gearbox casing itself is one of the most important components of the gear system, and it plays an important role in vibration and acoustical signal propagation, as studied in [14–18]. Therefore, its effect cannot be neglected and should be taken into consideration when modelling a gear transmission. Moreover, the validation of the dynamic vibration behaviors of a real gear transmission also requires to obtain the actual values of the physical properties of some important components, such as stiffness and damping ratios of bearings, shaft couplings and gearbox-fixing bolts, etc. However, these physical properties are mostly unknown and are affected by the working and mounting conditions. Therefore, theoretical or experimental evaluation of these critical parameters is often necessary.

In light of the review above, the goal of this paper is to propose a new dynamic model to simulate the vibration behaviors of a spur gear transmission with pitting and spalling defects. A gear contact model is proposed to account for the effects of tooth surface roughness changes and geometric deviations due to pitting and spalling. The proposed model considers the effect of gearbox casing, incorporates TVMS, time-varying load sharing ratio, dynamical tooth contact damping ratios, friction forces and friction moments. Experimental tests are performed to validate the proposed dynamic model under healthy cases as well as different fault conditions. The system physical properties (e.g. mass, mass moment of inertia) and mechanical parameters (e.g. stiffness and damping coefficients of bearings and bolts) used in the simulations were obtained by direct measurement or were calculated based on experimental tests combined with dynamic theories. The results were examined in both time and frequency domains, under different rotation speeds and fault severity conditions. Spectrum comparisons [19] are provided to identify the difference between damaged and healthy cases.

The paper is organised as follows. Section 2 develops the surface contact model based on mixed Elastohydrodynamic lubrication (EHL) theory with tooth pitting and spalling. Section 3 evaluates the time-varying mesh stiffness of gear tooth pairs. Section 4 establishes an advanced dynamic model of a spur gear transmission. Section 5 discusses the evaluation of the values of the stiffness and damping ratios of bearings and bolts of the gear systems. Section 6 validates the proposed dynamic model by comparing the simulated results with experimentally obtained vibration signals under different working conditions. Section 7 evaluates the effects of friction forces in gear dynamic models. Section 8 concludes the paper.

2. Gear contact model with tooth pitting and spalling

In practice, tooth pitting and spalling are normally first initiated on the smaller gear (which undergoes more revolutions and therefore more stress cycles) and close to the tooth pitch line [1], see Fig. 1. The size of what delineates pitting and spalling has not been uniformly defined and both terms are often used interchangeably. Based on [20,21], the size of pitting can range from 0.01 mm (micro-pitting) to 0.8 mm (macro-pitting) in diameter, and the size of tooth spall is considerably larger than tooth pitting.